INTERNATIONAL ASSOCIATION FOR
GREAT LAKES RESEARCH

J. Great Lakes Res. 11(4):462–477
Internat. Assoc. Great Lakes Res., 1985

IMPORTANCE OF TEMPORAL VARIABILITY TO THE DESIGN OF LARGE LAKE WATER QUALITY NETWORKS

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ABSTRACT. *Routine monthly sampling for a variety of chemical parameters has been conducted on Lake Ontario since 1968, as part of the Canadian Federal component to the Great Lakes Surveillance International Program. Analysis of the historical data has produced statistically ($P \leq 0.05$) homogeneous zones for a variety of surveillance parameters. In the present study, weekly sampling within one of the zones was performed at multiple depths. Analysis of the chlorophyll a, total phosphorus, and nitrate + nitrite nitrogen data indicated that differences as great as 20% can occur between samples taken at one metre versus a zero to twenty metre integrated value. Comparison of various monthly scenarios obtained from the weekly samples indicate that not only are the estimates and the description of seasonal cycles altered, but spurious trends can be established. Annual differences in mean concentrations as great as 35% can occur due to sampling artifacts. Details on the number of samples needed to provide statistically valid mean annual or seasonal values at various confidence limits for the studied parameters are presented.*
ADDITIONAL INDEX WORKS: Lake Ontario, monitoring, chlorophyll a, phosphorus, nitrates.

INTRODUCTION

The basic objective of a monitoring or surveillance program is to determine a mean value (seasonally or annually) for a variety of water quality variables. Subsequent comparisons of the mean values are then performed either spatially, to determine areas of significant deterioration, or temporally, to determine trends. Optimization of the water quality network is a crucial component of the program. The primary difficulty lies in designing a program with a sufficient number of stations to supply adequate spatial coverage, and to have an adequate sampling frequency, so that the desired confidence interval about the mean value for the various water quality variables can be achieved, all within a predetermined budget. This paper presents, as a case study, the Lake Ontario Surveillance Program. A review of program objectives, network design, comments regarding the importance of spatial and temporal variability, and recommendations on an upgrading of the sampling network are given.

Canada and the United States signed an Agreement on Great Lakes Water Quality in 1972 with the intention of preventing further pollution of the Great Lakes system caused by continuing population growth, resource development, and increasing use of water. Shortly after the Agreement was signed, the International Joint Commission (IJC), an investigatory and advisory body in matters concerning international waters, established the Great Lakes Water Quality Board to assist the Commission with its responsibilities. According to the 1972 Agreement, programs directed toward the achievement of the water quality objectives outlined in the Agreement would be in progress by 31 December 1975. As an annual objective surveillance and enforcement activities were established to: provide water quality trend information and to describe and quantify cause (loads) and effect (water qual-

ity) relationships to understand how the Great Lakes physical, biological, and chemical systems operate (GLWQA 1978). An open lake (federal) Surveillance Program, addressing the requirements in the Agreement, was designed for Lake Ontario by scientists at the Canada Centre for Inland Waters, Burlington, Ontario in 1974.

The original design for the Surveillance Program was seen as a multi-stage monitoring design. Data collected in the first stage would be critically analyzed to provide information on the best design for subsequent stages. This iterative process was established so that information obtained from one stage of the program would be used to design or verify the following stage. Systematic sampling with a random element approach was considered to be the best sampling strategy for Lake Ontario. Systematic sampling consists of selecting a unit at random from 1 to k and then selecting every kth unit thereafter. In the modified systematic sampling program presently used in surveillance, samples are taken monthly between March and December; however, the exact day of the month when sampling occurs is dictated by resource availability and thus often takes on a random component.

In lakes as large as Lake Ontario, nearshore areas receive tributary, point source, and diffuse source inputs of nutrients. These inputs can undergo coastal entrapment due to specific current patterns and thermal structures characteristic of inshore areas (Csanady 1970). As a result, nearshore environments often display significantly higher concentrations of inputs and greater variability than do the offshore areas (Beeton and Edmondson 1972). For these reasons the federal surveillance sampling locations, although designed to give an overall view of the lake, sampled the 2 to 10 km offshore area more intensively.

In 1974, eutrophication was considered to be the main issue of concern in the Great Lakes basin and the parameter list reflected this concern. Fifteen surveillance cruises were conducted on Lake Ontario in 1974. In subsequent years the cruise frequency was reduced; however, the station numbers (approximately 100) and locations were maintained (with some minor modifications, Fig. 1), so

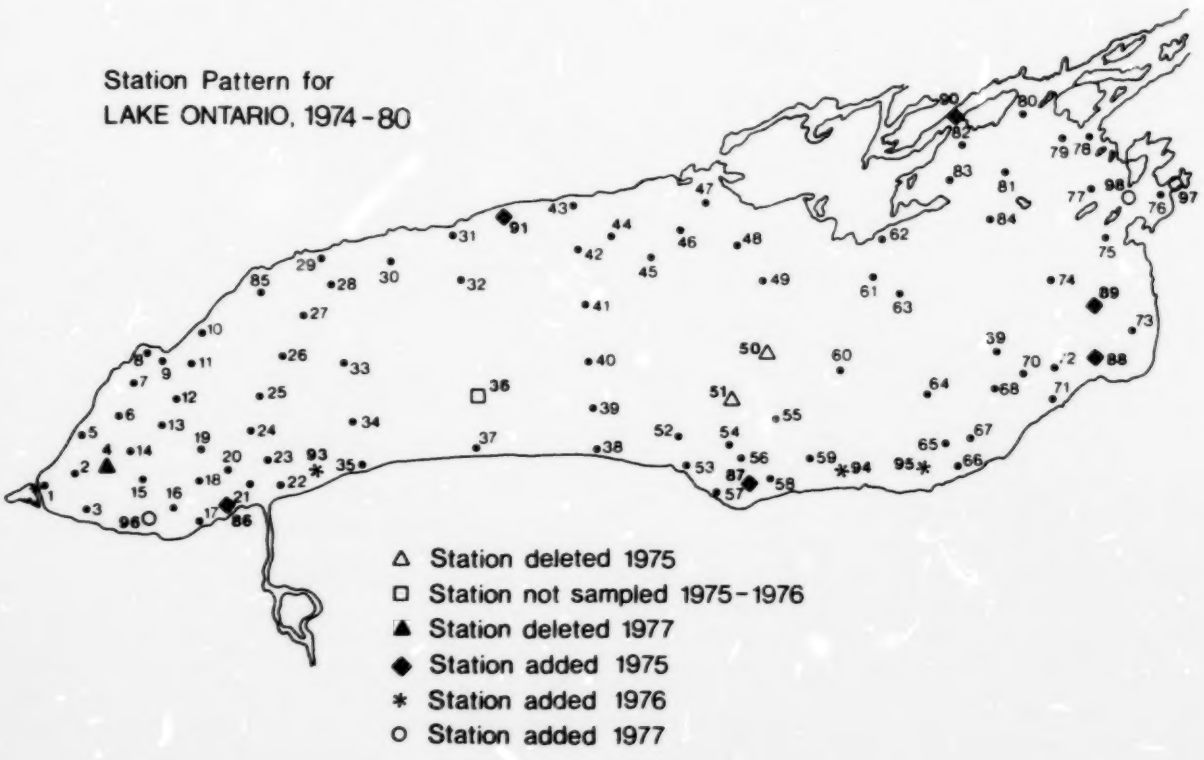

FIG. 1. Station location on Lake Ontario for the Surveillance Program.

that meaningful analyses on spatial variability and the establishment of statistically significant zones could be made. For more details on station locations, parameters measured, and sampling frequency for whole lake sampling of Lake Ontario see Kwiatkowski and Neilson (1983).

A regression model developed by El-Shaarawi and Kwiatkowski (1977) divided Lake Ontario into statistically homogeneous zones for a variety of biological and chemical parameters. The model transforms the original observations, so that the transformed values approximately satisfy the assumptions required for the application of the analysis of variance: i.e., the mean value can be expressed as a linear combination of the influencing factors; constancy of variance, additivity of the error term, and normality of distribution (El-Shaarawi and Shah 1978). An additive linear model with seasonal and spatial components was then fitted to the transformed data. A hierarchical classification procedure using estimates of spatial effects is then applied to divide the lake into statistically homogeneous zones. The model was used on chlorophyll *a* data to divide Lake Ontario in three zones referred to as offshore, nearshore, and point source (Kwiatkowski 1978). Each zone not only had a statistically ($p \leq 0.05$) different annual concentration of chlorophyll *a*, but also displayed a unique seasonal pattern (Fig. 2, Table 1). The model also showed that the temporal variability F(1) was approximately fifteen times greater than the spatial variability F(2) for chlorophyll *a* in 1976 (Table 1). This analysis (Table 1) demonstrated that the overall estimated mean concentration of chlorophyll *a* in Lake Ontario could easily be altered by simply moving stations from the offshore zone (mean concentration of 4.50 μg/L) to either the nearshore area (mean concentration 6.71 μg/L, a 50% increase) or to the point source area (mean concentrations 9.39 μg/L, a 110% increase).

In 1978, Kwiatkowski (1978) concluded that a more cost-efficient surveillance program on Lake Ontario could be designed by initiating a two network system. The first network would consist of the existing station network sampled approximately ten times per year (*i.e.*, monthly from March to November) for 2 consecutive years in each decade to reestablish the areal extent of the statistically homogeneous zones for each parame-

TABLE 1. Number of observations N, standard deviation S, coefficient of variation CV, mean $\bar{X}$, temporal variability F(1), and spatial variability F(2) for chlorophyll a on Lake Ontario.

Chlorophyll *a* (μg/L) Year	Zone	N	S	CV	$\bar{X}$	F(1)	F(2)
1976	1	733	2.80	62.22	4.50		
	2	228	2.14	40.83	6.71		
	3	22	4.03	42.92	9.39		
	whole lake	993	3.23	61.76	5.23	61.45*	4.86

*significant at ($P \leq 0.01$)
Table taken from Kwiatkowski (1978).

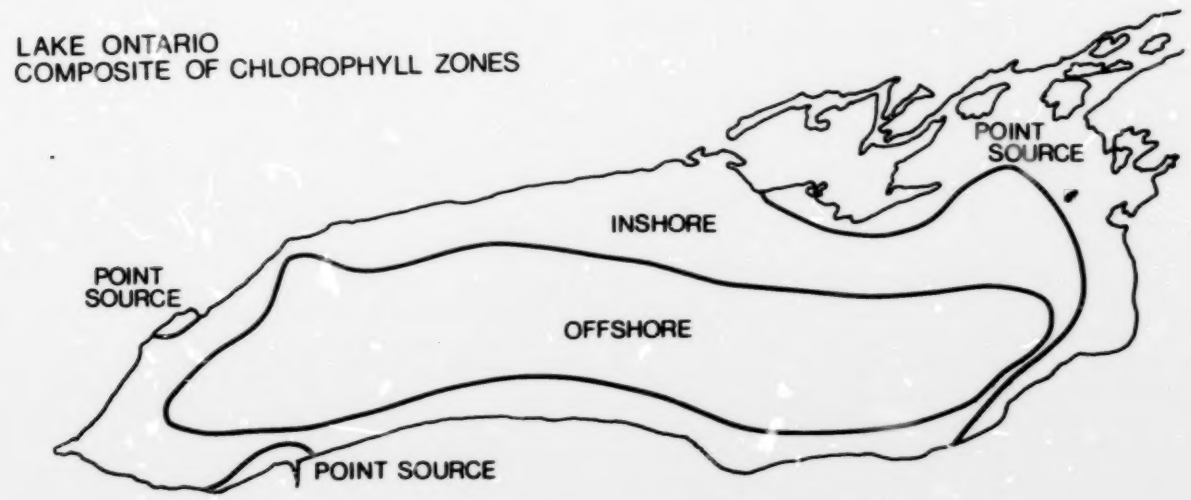

FIG. 2. Zonation of Lake Ontario produced with chlorophyll a data taken from Kwiatkowski 1978.

ter, or group of parameters. During the remaining 8 years within the decade the second network would consist of four whole lake cruises per year augmented by weekly sampling of two or three stations located in each of the statistically homogenous zones. Weekly sampling would provide a better definition to the seasonal cycle for the various parameters of interest. Once the seasonal cycle for a parameter was properly defined, temporal weighting could be applied to the calculation of annual mean or seasonal mean concentrations for the various water quality constituents (Kwiatkowski 1978). Trend analysis could then be performed through subsequent analyses of the annual or seasonal means.

In the present study three chemical parameters, chlorophyll a, total phosphorus (TP), and nitrate + nitrite nitrogen (NO_3 NO_2 –N), chosen because of their importance in the process of eutrophication (Vollenweider 1968) and because they have been monitored annually on Lake Ontario since 1974 as part of the Surveillance Program, were sampled weekly at one station located in the nearshore homogeneous zone. Evaluation of the data using commonly utilized data summary techniques indicated that significant variability exists spatially and temporally. The importance of this variability in relation to trend-in-time analysis and the description of the seasonal cycle as outlined in the objectives of the Surveillance Program is explained. Secondly, simple, straight forward statistics based on several simplifying assumptions are presented to evaluate various sampling frequency scenarios.

MATERIALS AND METHODS

Water samples were collected between 1000 and 1100 hours from six depths (1 m, 5 m, 10 m, 15 m, 20 m, 30 m, and 40 m) at a surveillance station located approximately 1.5 km from shore (Fig. 3) in 1979. This region was classified as nearshore by Kwiatkowski (1978). A 2-L Van Dorn sample was obtained at each depth on a weekly basis from mid-April to the end of November (ice free period). Chlorophyll *a* samples were kept in opaque bottles until returned to the laboratory. One litre of water was filtered within 2 hours of collection through a Whatman GF/C glass fiber filter under a vacuum not exceeding 180 mm of mercury for chlorophyll *a* analysis. When 100 mL remained, 10 drops of saturated $MgCO_3$ suspension was added and the filter was stored in a desiccator in a freezer. The filters were ground with a

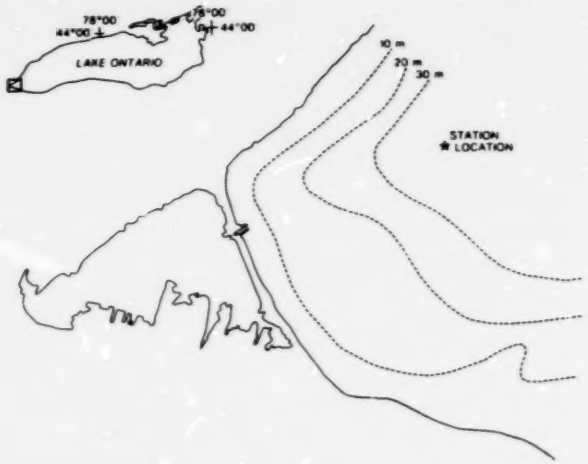

FIG. 3. Location of sampling station on Lake Ontario.

Teflon homogenizer for one minute in three mL of 90% acetone. The resulting solution was made up to 10 mL and allowed to stand for 3 minutes in the dark at room temperature to improve extraction of pigments. Samples were centrifuged for 10 minutes at 3,000 rpm and the chlorophyll *a* concentration was determined in μg/L spectrophotometrically using the SCOR/UNESCO equation (Strickland and Parsons 1968). The samples were also analyzed for pheopigments (pheophytin *a* plus pheophorbide *a*) using the analytical procedure described by Lorenzen (1967) and Yentsch (1970). All values reported in the present study are for corrected chlorophyll *a* and have units of μg/L.

Total phosphorus (TP) and nitrate + nitrite nitrogen (NO_3NO_2–N) samples were also collected with the Van Dorn sampler. NO_3NO_2–N samples were filtered through a 45 μm Millipore filter within 2 hours of collection and stored at 4°C until analyzed by an Auto Analyzer (Philbert and Traversy 1973). TP samples were acidified in the field and stored at 4°C until analyzed (Shiomi and Kuntz 1973). Temperature measurements were taken at each sampling depth with a YSI telethermometer and the values expressed as °C to the nearest 0.5 degree. All laboratory analyses were done within 2 months of collection.

Historically, publications on Lake Ontario surveillance data have reported values for the various variables at either discrete depths or as an integrated (0–20 m) value (Schroeder 1969).

In the present study integrated depth values for chlorophyll *a*, TP, and NO_3NO_2–N were calculated from the following equation.

$$C_{DW} = ((D_1 \times D_1) + ((C_1 + ((C_2 - C_1)/2.0)) \times (D_2 - D_1)) + ((C_2 + ((C_3 - C_2)/2.0)) \times (D_3 - D_2)) + \ldots + ((C_{n-1} + ((C_n - C_{n-1})/2.0)) \times (D_n - D_{n-1})))/D_n$$

where: C_{DW} is the depth weighted concentration from 0 to any chosen depth D.

$C_1, C_2, C_3 \ldots C_n$ are the concentrations of the given parameter at the corresponding $D_1, D_2, D_3 \ldots D_n$ sampling depths.

The matched pair t-test (Snedecor and Cochran 1967) was used to test for significant differences between the means of the various strata.

RESULTS

The objective of this paper is to discuss sampling frequency and its importance to the calculation of seasonal or annual means. However, for the sake of completeness, brief descriptions of the values obtained are presented here. Depth contouring obtained from the weekly sampling at 1, 5, 10, 15, 20, 30, and 40 m for temperature, chlorophyll *a*, TP, and NO_3NO_2–N for station 1 are given in Figures 4a, b, c, and d. For all parameters homogeneity with depth exists in the spring and fall periods. Thermal stratification commences at the end of May (Fig. 4a) and lasts through mid-October. At station 1, the thermocline was not stable throughout the summer months, and upwelling-downwelling events occurred through July, August, and September. An average thermocline depth, defined as the depth of maximum temperature change for this station, was approximately 15 m with ranges of 10 m during a July upwelling and 30 m during an August downwelling event. The maximum water temperature recorded was 19.8°C on 1 August.

The upwelling-downwelling events during the summer months had obvious effects on the three measured chemical parameters: chlorophyll *a*, TP, and NO_3NO_2–N. Chlorophyll *a* concentrations varied from a minimum of less than 2.0 µg/L in early spring and late fall to a maximum of 13.9 µg/L recorded at the 5-m depth on 27 June. In general, concentrations in the epilimnion ranged between 4 and 8 µg/L during the summer period. (Fig. 4b).

TP concentrations remained relatively constant throughout the study period. Maximum values occurred at the surface and at the bottom throughout the study period, with minimum values being found in the mid-water column (Fig. 4c). NO_3NO_2–N values were strongly influenced by the upwelling-downwelling events during August. Minimum values occurred in the epilimnetic waters for most of the summer period, with the exception of the early August period, when an upwelling event returned NO_3NO_2–N values in the epilimnion to a spring-fall maximum (Fig. 4d).

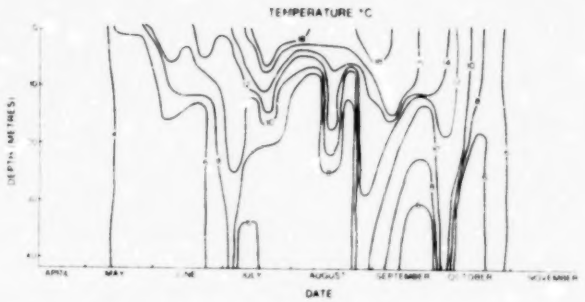

FIG. 4a. Temperature profiles obtained from weekly sampling at 1, 5, 10, 15, 20, 30 and 40 metres.

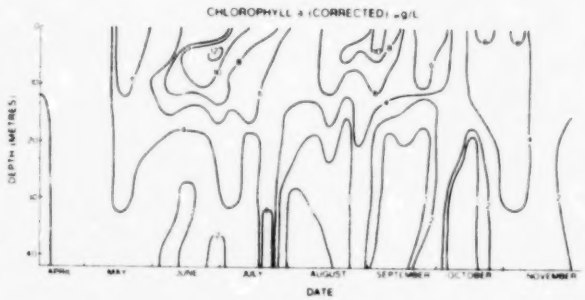

FIG. 4b. Chlorophyll a profiles obtained from weekly sampling at 1, 5, 10, 15, 20, 30, and 40 metres.

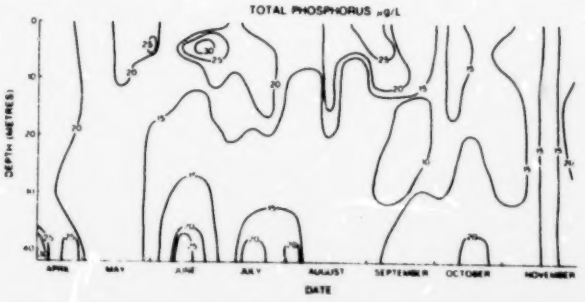

FIG. 4c. Total phosphorus profiles obtained from weekly sampling at 1, 5, 10, 15, 20, 30, and 40 metres.

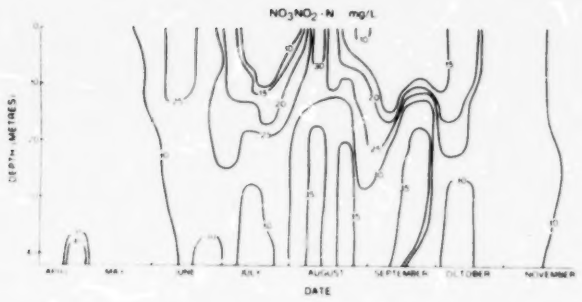

FIG. 4d. Nitrate–nitrite nitrogen profiles obtained from weekly sampling at 1, 5, 10, 15, 20, 30, and 40 metres.

A replotting of the chemical data in a more traditional form is given in Figures 5a, b, and c for the 1-m values, and the 0–15-m and 0–20-m calculated depth weighted values, for the three studied chemical parameters.

In general, maximum chlorophyll *a* concentrations were found at the 1-m depth with the exception of the June period when both the 0–15-m and 0–20-m concentration were higher (Fig. 5a). Three distinct peaks are observable in the data, with one occurring in May prior to the start of stratification, one in June after stratification, and one in September before fall overturn. Calculated arithmetic means and standard deviations for the entire sampling period as well as for the time period from the end of May to mid-October (summer stratification) for the 1 m, 0–15 m and 0–20 m depths are given in Table 2. Though the mean concentrations for chlorophyll *a* differ among the various strata examined, the coefficient of variation remains relatively constant for either the summer stratification ($\approx 26\%$) or for the entire sampling period ($\approx 37\%$) (Table 2). A 20% ($p \leq 0.01$) difference was found between the 1 m versus the 0–20 m arithmetic means for chlorophyll *a* during the summer stagnation period (Table 2). This difference was reduced to 17% ($p \leq 0.01$) when the arithmetic means were calculated for the entire sampling period.

TP concentrations were highly variable throughout the sampling period and no obvious seasonal pattern was observed (Fig. 5b). Both the minimum and maximum values occurred during August, the period of maximum upwelling-downwelling. Though the plot of the TP concentration at the 1-m depth varies from the plots of the 0–15 m and 0–20 m depth weighted concentrations, the arithmetic means for the three statistics are only minimally ($< 7\%$) yet significantly ($p \leq 0.05$) different (Table 2). Coefficient of variation values for the

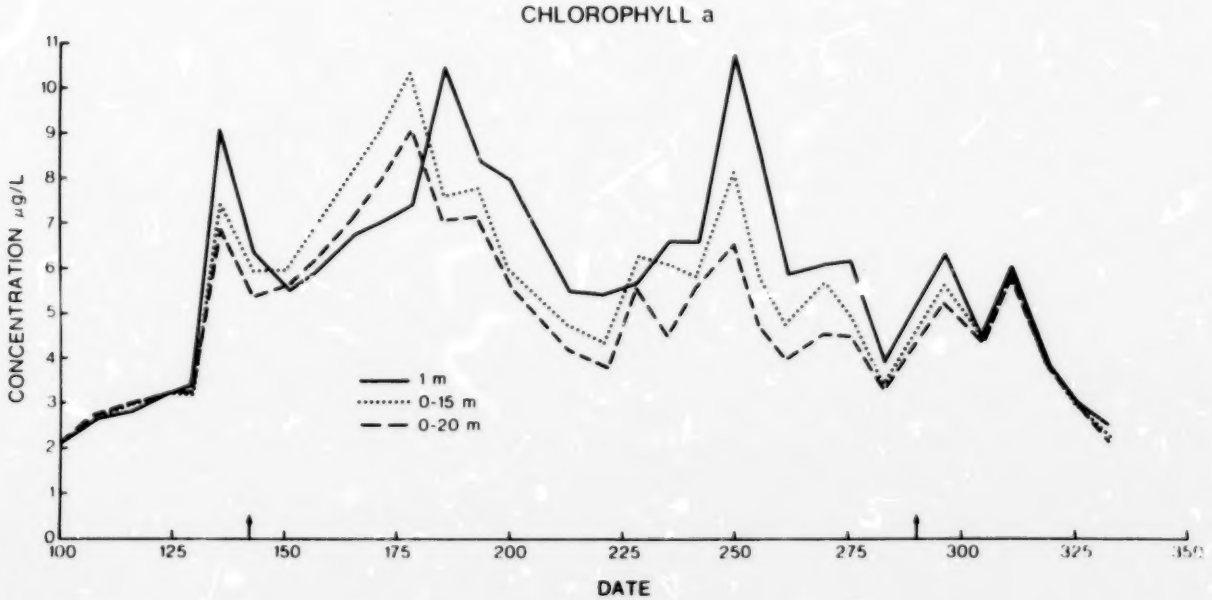

FIG. 5a. Chlorophyll a concentrations obtained for 1 m, 0–15 m (integrated), and 0–20 m (integrated). Period of thermal stratification exists between arrows (↑).

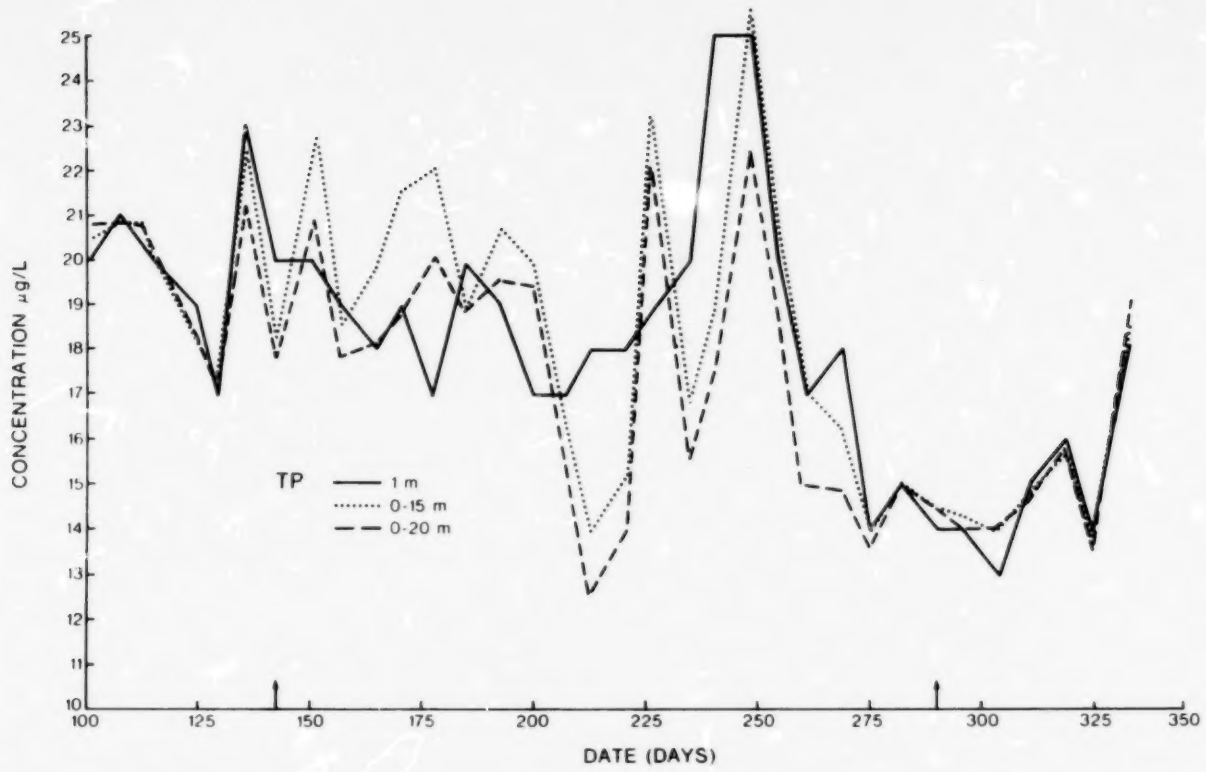

FIG. 5b. Total phosphorus concentrations obtained for 1 m, 0–15 m (integrated) and 0–20 m (integrated). Period of thermal stratification exists between arrows (↑).

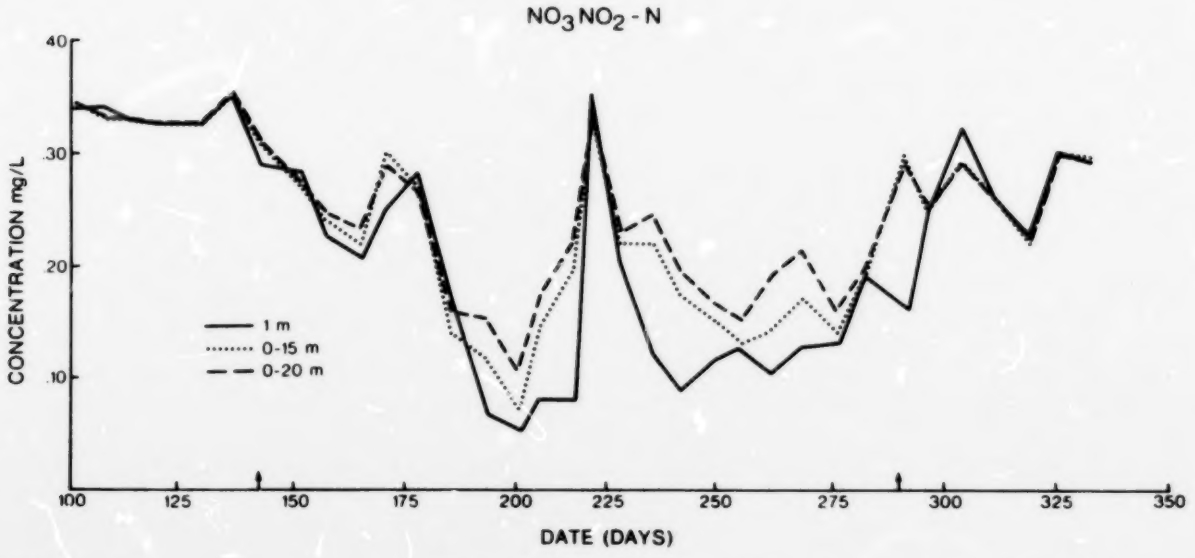

FIG. 5c. Nitrate–nitrite nitrogen concentrations obtained for 1 m, 0–15 m (integrated), and 0–20 m (integrated). Period of thermal stratification exists between arrows (↑).

TABLE 2. Number of observations N, mean $\bar{x}$, standard deviation (S) and coefficient of variation CV for measured parameters during summer stagnation (23/05–18/10) and for sampling season (11/04–29/11).

Parameter	Time Period	Depth	N	$\bar{x}$	S	CV	% differences in mean values 1 m	0–15 m	0–20 m
Chlorophyll *a*	23/05–18/10	1 m	20	6.81	1.72	25.26	—	—	—
(μg/L)	23/05–18/10	0–15 m	20	6.35	1.67	26.30	-7.24	—	—
	23/05–18/10	0–20 m	20	5.67	1.51	26.36	-20.11**	-11.99**	—
	11/04–29/11	1 m	32	5.81	2.23	38.38	—	—	—
	11/04–29/11	0–15 m	32	5.43	2.03	37.38	-7.00	—	—
	11/04–29/11	0–20 m	32	4.98	1.73	34.74	-16.67**	-9.04**	—
TP	23/05–18/10	1 m	21	18.8	2.6	13.83	—	—	—
(μg/L	23/05–18/10	0–15 m	21	18.9	3.2	17.02	0.53	—	—
	23/05–18/10	0–20 m	21	17.5	2.8	16.00	-7.43*	-8.00**	—
	11/04–29/11	1 m	34	18.2	2.9	15.93	—	—	—
	11/04–29/11	0–15 m	34	18.4	3.2	17.49	1.09	—	—
	11/04–29/11	0–20 m	34	17.4	2.8	16.09	-4.60	-5.75**	—
NO_3NO_2–N	23/05–18/10	1 m	21	.1694	.0864	51.00	—	—	—
(mg/L)	23/05–18/10	0–15 m	21	.1972	.0690	34.99	14.10**	—	—
	23/05–18/10	0–20 m	21	.2151	.0584	27.15	21.25**	8.32**	—
	11/04–29/11	1 m	34	.2169	.0970	44.72	—	—	—
	11/04–29/11	0–15 m	34	.2369	.0778	32.84	8.44**	—	—
	11/04–29/11	0–20 m	34	.2479	.0664	26.78	12.51**	4.44**	

*significant $p \leq 0.05$
**significant $p \leq 0.01$
As determined by a matched pair t test.

reported depths varied only slightly, both in terms of between depths or between data sites (i.e., summer stratification versus entire sampling period).

NO_3NO_2–N concentrations decreased steadily once the thermocline was formed. Values reached a minimum in July. The August upwelling-downwelling event returned NO_3NO_2–N concentration values throughout the epilimnion to levels approximating the spring maximum (Fig. 5c). Concentrations again decreased throughout the summer period and increased after stratification breakdown. The arithmetic mean concentration of NO_3NO_2–N at the 1-m depth, during the summer stratification period, was 21% ($p \leq 0.01$) lower than the calculated 0–15 m integrated mean for the same time period. The coefficient of variation values were at a maximum for the 1 m values (51 and 45) for both study periods. Integration of NO_3NO_2–N concentrations from 0–20 m approximately halved the coefficient of variation values (Table 2).

DISCUSSION

The Great Lakes International Surveillance Plan was designed to be a long term (>10 years) strategy to determine the impact of man's activities on the Great Lakes ecosystem (IJC 1976). The plan was to provide information on a yearly basis on the location, severity, areal or volume extent, frequency, and duration or non-achievement of set objectives, as well as to evaluate water quality trends. Information on water quality trends would assist in the development and application of predictive techniques for assessing impact of new developments and pollution sources. Management and policy decisions could then be developed, compared to predictive equations, and re-evaluated on an iterative basis to provide sound management strategy.

A wealth of information has been published on the location and areal and volume extent of various water quality parameters in the Great Lakes, indicating that the present Surveillance Plan has indeed fulfilled this objective. However, only a few studies have provided information on lake trends (Rockwell *et al.* 1979, Simons 1979, Chapra 1980, Dobson 1980, Fraser 1980, IJC 1980 and Kwiatkowski 1982). Reasons for the small number of publications on water quality trends (Wolman 1971) include:

i) – Water quality records are often short in duration.
ii) – Techniques and detection limits of analytical methods often change over the years.
iii) – Sampling location and frequency change between years.
iv) – Natural background variability often hides water quality trends.

Points i, ii, and iii have been resolved in the Surveillance Plan by developing a bi-laterally coordinated surveillance programme designed to produce consistent, statistically analyzable data. Spatial variability, for most parameters, has been adequately addressed, so that statistically homogeneous zones can be established (El-Shaarawi and Kwiatkowski 1977, Kwiatkowski 1978). Temporal variability, though deemed important, has for the most part not been investigated by the federal component of the Surveillance Program. A large portion of the costs of operating the surveillance network is due to sampling. Thus management has been reluctant to make costly changes to the network without sufficient proof that the changes are needed.

As previously stated the sampling strategy presently used in the Surveillance Plan is systematic sampling with a random element (i.e., data collected every month between March and December). If a truly regimented systematic sampling program were used, samples would be taken the same week of every month. Due to the fact that it takes 3 to 4 days to sample Lake Ontario, a sample frequency of less than 1 week is impractical.

The data in the present study were taken in 1979 at one surveillance station, previously defined as being representative of nearshore conditions. Four different sampling scenarios based on systematic design are tabulated in Table 3, with k equal to 1 month in each of the four cases, and only the starting sample date changed (i.e., 1st, 2nd, 3rd, or 4th week of the month). For the majority of sampling scenarios tested, differences between annual mean concentrations were less than 10%. The obvious exception was for chlorophyll *a* sampled at the 1-m depth where a maximum difference of 34% was found between sampling the last versus the 4th week. Indeed a statistically significant ($p \leq 0.001$) decreasing trend exists for the chlorophyll *a* annual mean values obtained at the 1-m depth (if weekly is substituted by annually in Table 3).

A second observation of the various sampling scenarios is that the seasonal cycles are greatly altered by the timing of the sampling cruises (Figs. 6a, b and c). For chlorophyll *a*, sampling the 1st week of every month yielded a typical bimodal response, with spring and fall maxima occurring in July and September. Sampling the 2nd week of every month produced a trimodal response with a spring (May), summer (July), and fall (September) maxima, while sampling in the 3rd week produced a unimodal summer maximum for chlorophyll *a* (Fig. 6a). Interpretations of these various seasonal distributions have ranged from:

1) A bimodal pattern is typical of large temperate lakes (Glooschenko *et al.* 1974, Kwiatkowski 1978).
2) The trimodal cycle is the result of complex circulation patterns combined with increase nutrient input resulting in planktonic shifts (Glooschenko *et al.* 1972).
3) The lake is a typical, deep cold water lake, with the lag in the spring peak (until July producing a unimodal peak) being due to deep mixing and low water temperatures (Glooschenko *et al.* 1972).

A variety of descriptions for various seasonal cycles of phytoplankton biomass as measured by chlorophyl *a* are given by Glooschenko *et al.* 1973,

TABLE 3. Number of observations (N), mean ($\bar{x}$), and standard deviation (S) based on a systematic sampling strategy with k = 1, 2, 3 and 4 weeks.

		Week of Month											
		1st week			2nd week			3rd week			4th week		
Parameter	Depth	N	$\bar{x}$	S	N	$\bar{x}$	S	N	$\bar{x}$	S	N	$\bar{x}$	S
Chlorophyll *a*	1 m	7	6.84	2.76	8	6.01	2.55	8	5.75	1.85	8	5.10	1.72
(μg/L)	0–20 m	7	5.32	1.45	8	5.10	1.91	8	4.87	1.66	8	4.87	2.12
TP	1 m	7	18.4	3.6	8	18.7	2.5	8	17.8	2.7	8	18.6	3.4
(μg/L)	0–20 m	7	17.0	3.2	8	18.9	2.6	8	16.8	2.7	8	17.6	3.0
NO_3NO_2	1 m	7	.2259	.0918	8	.2144	.0978	8	.2086	.1068	8	.2245	.1066
(mg/L)	0–20 m	7	.2354	.0755	8	.2358	.0758	8	.2549	.0749	8	.2582	.0496

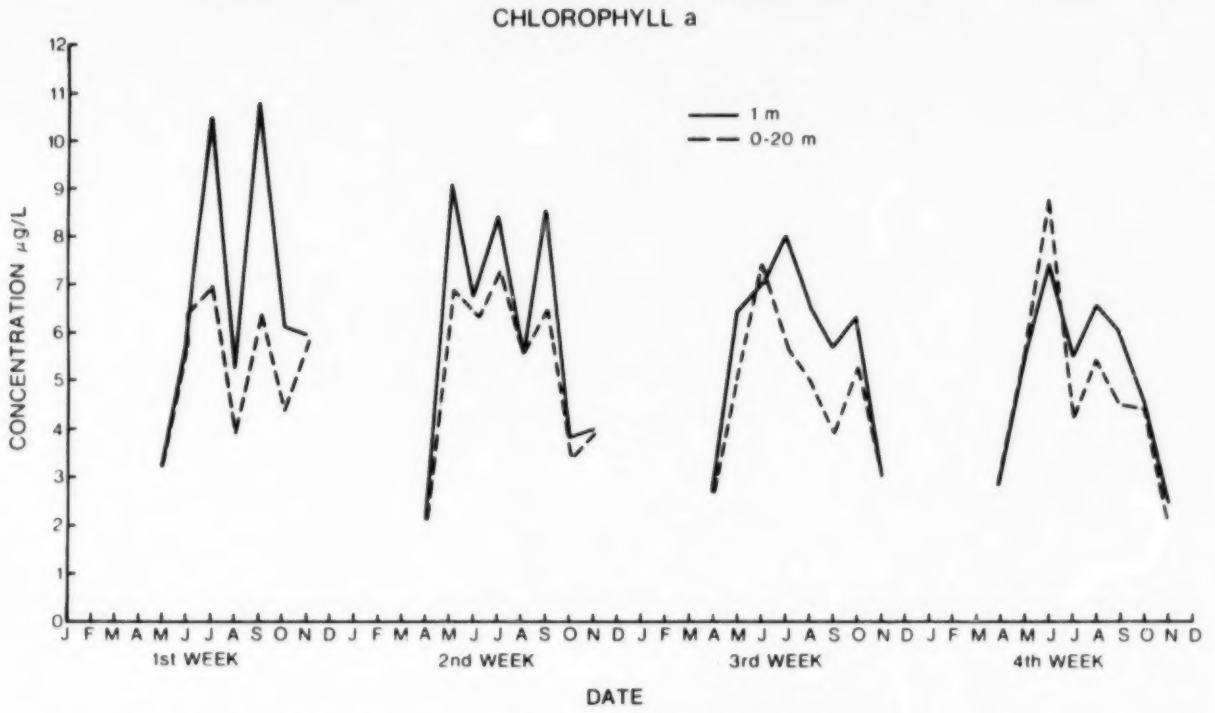

FIG. 6a. Seasonal cycles obtained for chlorophyll a with varying sampling scenarios.

Kwiatkowski 1980, Munawar and Munawar 1976, Munawar *et al.* 1974, and Vollenweider *et al.* 1974.

TP concentrations obtained from the 1st and 4th week indicate that a large August or September peak occurs, while samples from the 2nd week indicate a bimodal pattern. A continuous decline in TP concentrations from spring to late fall (Fig. 6b) is obtained from sampling the 3rd week. Comparison of 3 years of TP data from Lake Ontario indicated that the 1977 seasonal pattern was significantly different from the typical seasonal pattern typified by the 1976 sampling (Fraser 1980). The difference was attributed to summer and fall production dynamics and sedimentation rate changes even though no production dynamics or sedimentation rate data were available (Fraser 1980). A normal TP cycle for Lake Ontario is for spring values of 22.0-23.0 µg P/L to be reduced by 3–4 µg P/L by August or September and then increased due to overturn (thermal) and mixing to near spring values over the winter (Fraser 1980). Further descriptions and explanations of seasonal cycles for TP in Lake Ontario can be found in Gachter *et al.* 1974, Shiomi and Chawla 1970, and Stadelmann and Fraser 1974.

A summer minimum occurs in NO_3NO_2–N concentration (possibly a result of phytoplankton uptake) when samples are obtained from the 3rd or 4th week of the month (Fig. 6c). However, sampling of the 1st week results in a midsummer (August) maximum. Typical seasonal values for NO_3NO_2–N in Lake Ontario can be found in Gachter *et al.* 1974 and Stadelmann and Fraser 1974.

Apparently a great deal of care must be exercised when dealing with monthly data to ensure that over-interpretation does not occur. Several years worth of data are needed to ensure that the seasonal cycle is indeed due to lake morphometry, trophic status, a physiological response to a hierarchy of physico-chemical environmental variables, or simply a *sampling artifact*. Seasonally corrected trend-in-time equations were applied to monthly means for five commonly measured surveillance parameters collected between 1974 and 1980 (Kwiatkowski 1982). Offshore areas produced seasonally corrected trend-in-time equations with more significant coefficients than did nearshore areas, indicating that the offshore areas had more stable seasonal cycles. Temporal variability, like spatial variability, is dependent on the sample location. Thus, in order to determine trend-in-time, in

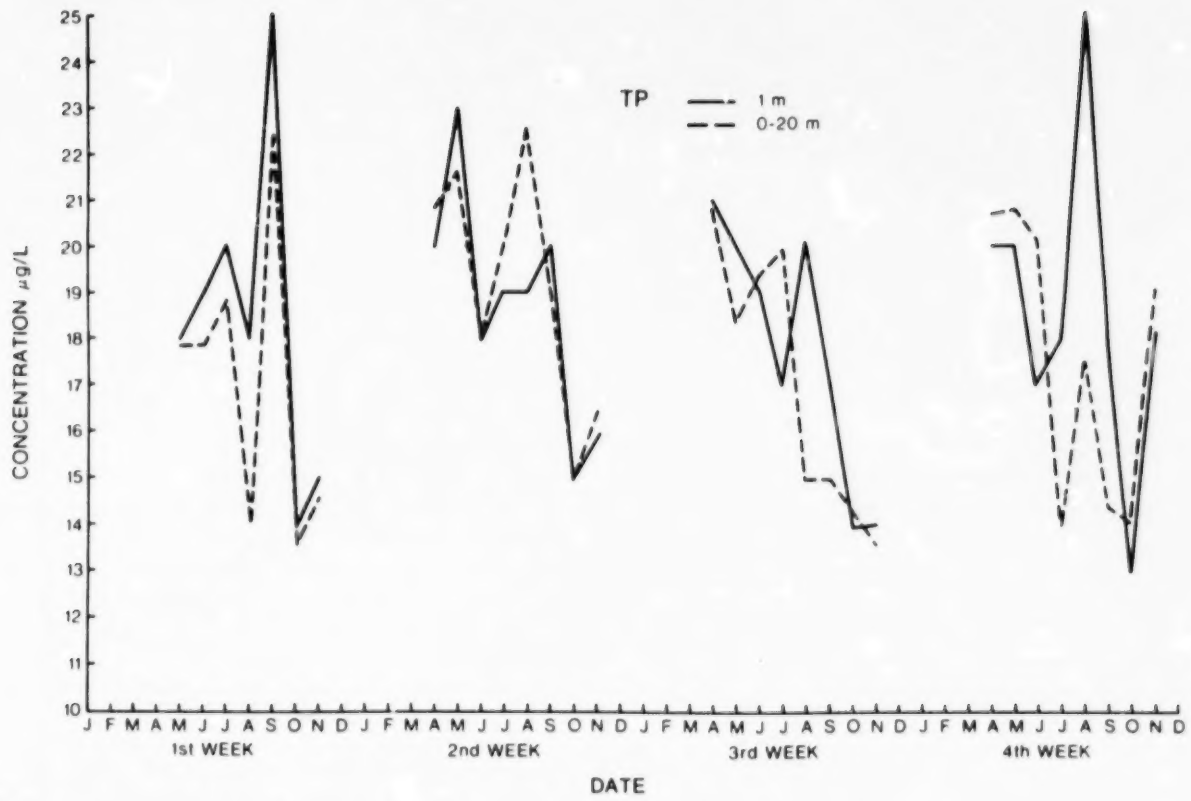

FIG. 6b. Seasonal cycles obtained for total phosphorus with varying sampling scenarios.

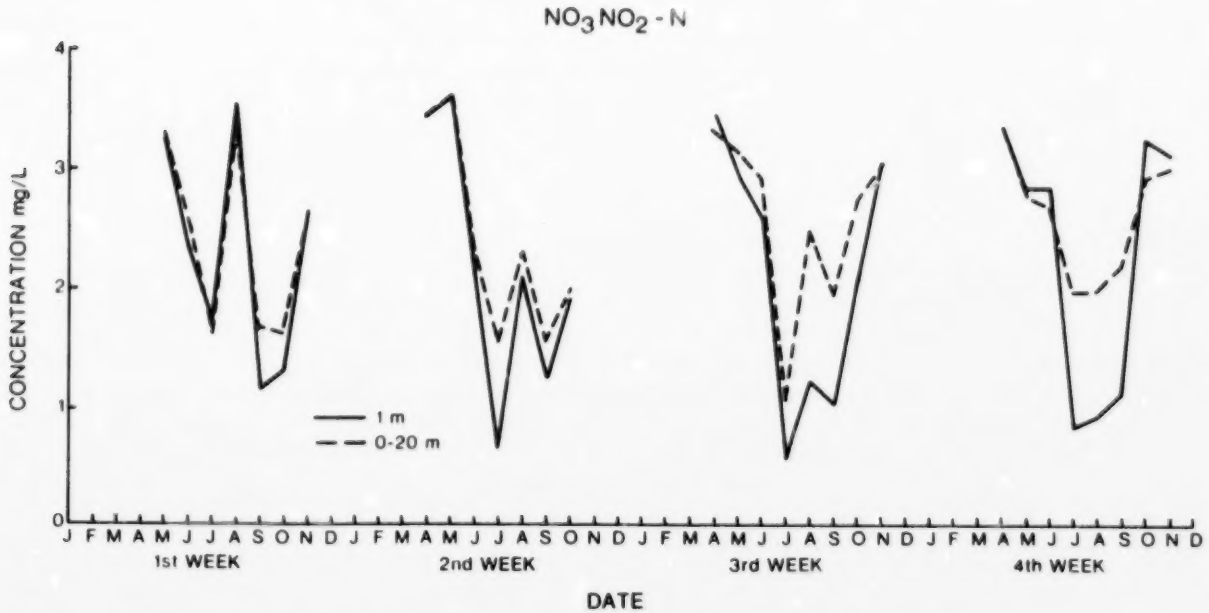
NO_3NO_2 - N
CONCENTRATION mg/L
4
3
2
1
0
1 m
0-20 m
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
1st WEEK
2nd WEEK
3rd WEEK
4th WEEK
DATE

FIG. 6c. Seasonal cycles obtained for nitrate + nitrite nitrogen with varying sampling scenarios.

the presence of the seasonal cycle, it is necessary to divide not only the lake into homogeneous zones, but the year into discrete time intervals (i.e., spring, summer, fall, and winter) and then determine the long-term variation in the mean of each zone, for each time interval.

Design of a suitable monitoring network to detect the trend of a given water quality parameter is a continuous iterative process. Data collected from an existing network with a fixed station location, parameter list, and sample frequency are transformed through the application of statistical techniques into information which assists in the redesigning of the existing network. Lettenmaier (1977) has stated that the two most common trends in environmental work are step and linear. A step trend is an instantaneous change in the mean level at a point in time. A linear trend is simply an increase or decline in the mean level through time. In large lakes such as Lake Ontario (with a volume of 1,720 km^3 and with a mean retention time of 7.8 years), an instantaneous change in a water quality trend is a virtual impossibility. Thus, for Lake Ontario, the linear trend has become the accepted technique for time series analyses and the most common statistic unit used in the trend detection has been the mean ($\bar{x}$) value. A hypothetical equation for a linear trend, for any given parameter x within the surveillance network, can be written as:

$$y_{Tn} = A_{To} + Bx_T + e_T \quad (1)$$

where: Y_{Tn} is the predicted concentration of parameter x at year Tn.
A_{To} is the initial concentration of parameter x at the start of the study, i.e., time = 0.
B is the slope of the equation, i.e., rate of change with time.
$\bar{x}_T$ is the mean calculated concentration of parameter x for year T.
e_T is a normal random variable with mean 0 and variance σ^2.

Mathematically, the mean concentration ($\bar{x}_T$) can be represented by the following equation:

$$\bar{x}_t = \frac{1}{n} \sum_{n=1}^{T} x_t \quad (2)$$

where: T is the period of consideration (for the calculation of annual means, T will be one year).
x_t is the concentration of the parameter at time t.
n is the number of observations.

A linear trend in itself is composed of two major components. The actual trend or determinist component and a random or stochastic component (e_T). Interaction of the diurnal and seasonal cycles, with the hydrograph of the lake, results in a large variability being associated with $\bar{x}_T$, the annual mean concentration. If this variability around the annual mean value can be reduced then the deterministic component of the linear trend can be increased. Thus the ultimate objective is to select a sampling frequency which will yield an estimate of the annual mean ($\bar{x}_T$) within a predescribed degree of accuracy.

Numerous studies have utilized confidence width calculations for the establishment of sampling frequencies in water quality monitoring (Mandel 1964, Green 1979, Ward *et al.* 1979, Dunnette 1980, and Nelson and Ward 1981). The simplest case of determining a sampling frequency would be to take one station, one variable, and determine the sampling frequency required to produce the desired confidence width about the annual or seasonal mean. Assuming that the samples are independent and randomly obtained, and that the sample mean is normally disturbed, a confidence interval about the true mean μ can be expressed as:

$$\bar{x} - Z_{\alpha/2} \text{ var } (\bar{x})^{1/2} \leq \mu \leq \bar{x} + Z_{\alpha/2} \text{ var}(\bar{x})^{1/2} \quad (3)$$

where: $\bar{x}$ is the sample mean as given in equation 2
$Z_{\alpha/2}$ is the standard normal deviate corresponding to a probability of $\alpha/2$
var ($\bar{x}$) is the variance of the sample mean, i.e.:

$$\text{var } (\bar{x}) = \frac{\sigma^2}{n} \quad (4)$$

where: σ^2 is the true population variance and n is the number of samples.

By substituting equation (4) into (3) and rearranging the terms:

$$n \geq \frac{Z^2_{\alpha/2}\sigma^2}{(\mu - x)^2} \quad (5)$$

where n is the number of samples needed to obtain an estimate of the mean with a known level of confidence.

Substituting σ^2 (the population variance) by S^2 (the sample variance as defined in equation 6), necessitates the replacement of $Z_{\alpha/2}$ by the Student's "t" statistic

$$S^2 = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2 \qquad (6)$$

If the difference between the population mean (μ) and the sample mean ($\bar{x}$) is replaced by L, equation 5 can be rewritten to:

$$n \geq \frac{t^2_{\alpha/2} S^2}{L^2} \qquad (7)$$

Each of the three studied parameters, chlorophyll *a*, TP, and NO_3NO_2-N, was divided into three temporal strata [i.e., the spring (isothermal), the summer (stratified), and the fall (isothermal) periods], as well as three spatial strata (i.e., 1 m, 0–15 m, 0–20 m). The numbers of samples needed to detect a 10% change and a 20% change (numbers in brackets) at the 90%, 95%, and 99% confidence limits, for each strata, are given in Table 4. The number of samples needed to estimate mean values for any given strata differs dramatically between parameters, with chlorophyll *a* (the biological parameter) requiring the maximum sampling effort. Division of the data set into strata, either temporally (by season) or spatially (verti-

TABLE 4. Number of samples needed to detect a 10% or (20%) change in mean value for sampled parameters, for temporal strata (spring, summer and fall), and spatial strata (1 m, 0–15 m, 0–20 m).

Parameter	Depth	Season*	Confidence level 90%	95%	99%
Chlorophyll *a*	1 m	spring	171(43)	279(70)	687(172)
		summer	19(5)	28(7)	52(13)
		fall	49(12)	81(20)	199(50)
	0–15 m	spring	116(29)	189(47)	464(116)
		summer	21(5)	30(8)	56(14)
		fall	47(12)	76(19)	187(47)
	0–20 m	spring	89(22)	145(36)	357(89)
		summer	21(5)	31(8)	59(15)
		fall	44(11)	71(18)	176(44)
TP	1 m	spring	4(1)	7(2)	16(4)
		summer	6(1)	8(2)	16(4)
		fall	5(1)	7(2)	17(4)
	0–15 m	spring	4(1)	6(1)	14(4)
		summer	8(2)	12(3)	23(6)
		fall	5(1)	7(2)	17(4)
	0–20 m	spring	3(1)	4(1)	11(3)
		summer	8(2)	11(3)	21(5)
		fall	6(1)	9(2)	21(5)
NO_3NO_2-N	1 m	spring	1(1)	1(1)	3(1)
		summer	77(19)	113(28)	210(52)
		fall	16(4)	25(6)	59(15)
	0–15 m	spring	1(1)	1(1)	2(1)
		summer	36(9)	53(13)	99(24)
		fall	4(1)	7(2)	16(4)
	0–20 m	spring	1(1)	1(1)	2(1)
		summer	22(5)	32(8)	60(15)
		fall	4(1)	7(2)	15(4)

*spring is defined as 11/04–23/05
summer is defined as 23/05–18/10
fall is defined as 18/10–29/11

cally through the water column), also alters the sampling requirements (Table 4). Sample frequencies for the spring period for the chemical parameters NO_3NO_2-N and TP are significantly lower in comparison to the biological parameter chlorophyll *a*. Integration of the sample (0–20 m) lowered the sample requirement for NO_3NO_2- and chlorophyll *a*, but had little effect on TP, when compared to a discrete 1m sample.

The values given in Table 4 for the number of samples needed to estimate the mean, within given degrees of accuracy, are not absolute. They represent at best "guestimates." There are several reasons for this. A minimum of 30 samples is needed so that the population variance can indeed be estimated by the sample variance (Spiegel 1961). Also, the above analysis assumes no serial correlation. Serial correlation may be thought of as redundancy of information and results from the fact that samples taken close together in time are often correlated. This redundancy in successive observations means less information is obtained from the data than can be expected from independent samples. As a result the confidence limit associated with the mean value is indeed larger than indicated by the statistics. In water quality populations, the degree of correlation generally increases as samples are taken closer together in time (Loftis and Ward 1980, Lettenmaier 1978, Sanders *et al.* 1983). Sanders *et al.* (1983) indicated that a large degree of redundancy in observations exists for data collected 2 days apart, while observations spaced 30 days apart are nearly independent. Kwiatkowski and El-Shaarawi (1977) indicated that 1st order autocorrelations existed for a variety of chemical and physical parameters measured on a semimonthly basis on Lake Ontario. Loftis and Ward (1978) have rewritten equation 4, the calculation of the variance of the sample mean, to include serial correlation. However, in order to estimate the n-1 auto correlation coefficients, it is necessary to have considerably more than n data points (Nelson and Ward 1981).

It has been previously observed that seasonally corrected trend-in-time equations for offshore areas resulted in higher regression coefficients than corrected trend-in-time equations for nearshore areas, indicating that offshore areas had a more predictable seasonal pattern than did the nearshore areas (Kwiatkowski 1982). Apparently from the data presented, monthly sampling, unless done over an extended period of time, is inadequate for the calculation of the seasonal cycle, and therefore inadequate for trend detection of yearly data sets. This can simply be overcome by applying trend analyses to only seasonal (i.e., spring, summer, fall, or winter) data. From Table 4 it is apparent that two to three spring cruises are sufficient to detect a 20% change in TP with a 95% confidence limit, and a 10% change in NO_3NO_2-N with a 99% confidence limit, for the nearshore region. If this approach is adopted, then sampling of the other time periods becomes an expensive redundant effort.

If the ecosystem concept, as described in the GLWQA (1978), is to be truly applied to Lake Ontario, intensive lake sampling should be done in 2 consecutive years in each 10-year period as suggested by IJC (1976) to re-establish the areal extent of each statistical zone. During the remaining 8 years, four whole lake cruises per year should be done. Sampling should start in winter to obtain information on winter conditions. The other cruises could then be done in April (to get the spring peak), August (for mid-summer conditions), and October (for the fall peak). Due to the fact that each statistical zone established displays a different seasonal cycle, especially with regard to the spring peak, it is mandatory that the seasonal cycle be properly defined for each zone. Two or three continuous monitoring stations which are capable of taking weekly samples should be established in each statistical zone. Once the seasonal cycle has been properly defined a temporal weighting can be applied to each statistical zone. Sampling of point source areas, or areas traditionally sampled by provincial or state governments, may indeed require daily sampling to properly describe the seasonal cycle. No doubt coordination of the federal surveillance programs (Canadian and American) with the provincial and state governments would be very helpful in this matter. It is believed that similar analyses of the other Great Lakes surveillance data sets are needed. The analysis of these data sets, by parameter, with respect to station pattern and cruise frequency could then be done to produce sound (cost/information) programs.

The data base presented in this paper is inadequate to determine the effect of either spatial or serial correlation. However, through the application of some simplifying assumptions (i.e., independence of observations, and sample variance equals population variance for the three temporal strata), data are presented which indicate that detection of trends in water quality parameters of large lakes requires not only an understanding of the aquatic ecosystem but also the application of

sampling theory to ensure that large quantities of data over an extended time period are not needlessly collected.

ACKNOWLEDGEMENTS

The author is indebted to Dr. A. H. El-Shaarawi, Dr. D. Haffner, D. E. Campbell, and R. Stevens for their helpful comments regarding this manuscript, and Dr. W. S. Gardner and D. M. Dolan for their constructive reviews.

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